Using of Transmission Line Matrix Method and Mode Matching Approach for Simulation of MMICs

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Abstract—**The exact modelling of the properties of transmission line structures in microwave monolithic integrated circuits (MMICs) requires full-wave modelling of the electromagnetic field in the semiconductor and insulator regions as well as within the conductors. The transverse dimensions of the transmission structures at the frequency above 10 GHz are comparable to the skin depth. Therefore the accurate simulation of the electromagnetic field inside the conductors is necessary. In this paper we combine the transmission line matrix (TLM) and mode matching (MM) methods for full-wave analysis of transmission lines and discontinuities in MMICs.**

Keywords— **Microwave Monolithic Integrated Circuits (MMICs), Damascene Technology, Mode Matching (MM) Method, Transmission Line Matrix (TLM) Method.**

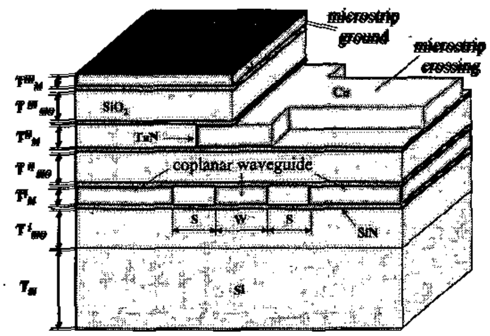

Fig. 1. Schematic view of the multilayered MMIC in Damascene technology.

I. Introduction

The application of copper as conductor material and the use of damascene technology is a promising way for future realization of highly integrated MMICs for frequencies of operation up to several 10 GHz. Compared to aluminium, copper exhibits significantly lower electro-migration, better electrical and thermal conductivity ([1], [2]). The higher current density achievable in copper transmission lines allows a decrease in the cross-section of the conductors. Damascene technology allows to reduce the size of transmission lines down to 0.2 μm width and 0.2 μm height. The dimensions of the conductors are comparable to the skin depth. Therefore an accurate simulation and optimization of the transmission structures in MMICs requires full-wave modelling of the electromagnetic field also inside the conductors.

Usual design tools for planar circuit design are not applicable, as most of them do not consider finite thickness of the metallization and loss appropriately. For methods working in time domain the required time step is very small, therefore these methods are not efficient due to high computational effort and high memory consumption.

In this paper we describe the combination of a frequency domain MM method for the modelling of homogeneous coplanar waveguide (CPW) structures with the time domain TLM method for the simulation of CPW discontinuities. The MM approach allows an accurate and efficient computation of the loss and dispersion properties of the homogenous structures ([3], [4], [5]), whereas the TLM method is advantageous for the modelling of discontinuities of arbitrary shape ([6], [7]).

II. Hybrid TLM-MM Approach

The MMICs in Damascene technology exhibit a multilayered structure containing various transmission line structures, i.e. coplanar waveguides (CPWs), striplines, microstrip lines, conductor backed CPWs and diverse discontinuities, e.g. crossings, right angle bends and T-junctions (see Fig. 1). Such Damascene structure consist of many thin layers like diffusion barriers, inversion layers, channel stoppers, trenches etc. Their influence on propagation characteristics should be taken into account. In transmission lines with strip width and height in the skin depth's order of magnitude, conductor losses influence the propagation characteristics severely, too.

One of the most efficient methods for numerical simulation of such homogeneous two-dimensional (2D) structures is the frequency domain based mode matching method. The fields inside the conductors, playing an important role, are fully taken into consideration.

Fig. 2 shows a CPW in Damascene technology inside a rectangular box with perfect electric conducting walls. For simulation of the quasi-TEM mode propagation only half of the structure has to be considered due to the symmetry in the xy-plane. The CPW cross section is subdivided into layers. In the layer i for a wave propagating in positive z-direction, the electric and magnetic fields $\boldsymbol{E}^i$ and $\boldsymbol{H}^i$ may be expanded in an infinite sum of partial wave components. Taking m eigenmodes into account in the layer i, we get :

$$\boldsymbol{n}_y \times \boldsymbol{E}^i = \sum_m \sum_n \boldsymbol{n}_y \times \boldsymbol{e}^i_{mn}(x) \sqrt{Z^i_{mn}} \cdot \\ \cdot \left[A^i_{mn} e^{jk^i_{ymn} y} + B^i_{mn} e^{-jk^i_{ymn} y} \right] e^{-jk^i_{zm} z} , \qquad (1)$$

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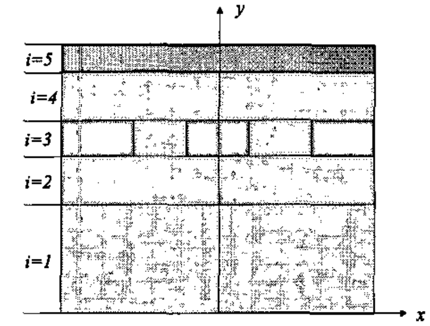


Fig. 2. The CPW cross section in Damascene technology.

$$n_y \times H^i = \sum_m \sum_n n_y \times h^i_{mn}(x)\ \sqrt{Y^i_{mn}}\ \cdot$$
$$\cdot \left[A^i_{mn} e^{jk^i_{ymn}y} - B^i_{mn} e^{-jk^i_{ymn}y}\right] e^{-jk^i_{zm}z}\ , \qquad (2)$$

where e^i_{mn} and h^i_{mn} are the vector–valued expansion functions for the electric and magnetic field respectively. The vector n_y is the unit vector in y-direction. $Z^i_{mn} = (Y^i_{mn})^{-1}$ are real normalization constants. In the computation the field expansion must be truncated to a finite number of partial waves n.

The field expansions in two neighboring layers i and j are matched by using method of moments (MoM) to the tangential field continuity conditions at their horizontal boundaries:

$$n_y \times (E^i - E^j) = 0\,,$$
$$n_y \times (H^i - H^j) = 0\,. \qquad (3)$$

By combining all continuity equations and boundary conditions at the waveguide walls sufficient relationships are obtained to determine the complex propagation constants k_{z_m}, and the unknown partial wave amplitudes of the fundamental and higher-order modes.

The S-parameters of the m^{th}-eigenmode of a CPW line segment of length l are

$$S_m = \frac{1}{c_m}\begin{bmatrix} (Z^2_{W_m} - Z^2_0)\sinh k_{z_m} l & 2Z^2_{W_m} Z^2_0 \\ 2Z^2_{W_m} Z^2_0 & (Z^2_{W_m} - Z^2_0)\sinh k_{z_m} l \end{bmatrix}, \qquad (4)$$

where

$$c_m = 2Z^2_{W_m} Z^2_0 \cosh k_{z_m} l + (Z^2_{W_m} + Z^2_0)\sinh k_{z_m}\ .$$

Here Z_0 is the reference impedance and Z_{W_m} is the wave impedance of the m^{th}-eigenmode of a CPW.

The transmission line matrix method is a well-established technique for solving of electromagnetic problems in the time domain. In TLM, the electromagnetic field is represented by wave amplitudes instead of electric and magnetic field components. The wave amplitudes are related to transverse electric and magnetic field components. TLM models electromagnetic structures by a network of interconnected transmission lines and employs a discretized form of Huygens model of wave properties in the time domain. The versatility of the TLM method allows straightforward calculation of complex structures. However generally, if structures with highly nonuniform regions and/or curvilinear structures are under consideration, variable and curved meshes are required in order to insure moderate computer run time and storage.

At a simulation by means of TLM the structure is excited with a Gauss pulse. The frequency characteristics of the structures , for example S-parameters, can be determined by Fourier transformation of the time response or system identification method.

The hybrid TLM-MM method is understood as a combination of the TLM and MM methods in the frequency domain. The homogenous transmission structures are simulated with the MM. For the analysis of the complex discontinuities the TLM is used. This hybrid method allows to reduce the computation time and the memory requirement for a passive structure simulation in relation to 3D methods. In TLM-MM the losses in the strip lines because of skin effect are taken completely into account.

If only the fundamental mode is taken into account two methods can be effective combined by mean of S-parameters in (4). The field distribution obtained by TLM method can be expanded into the eigenmodes of the specific section S

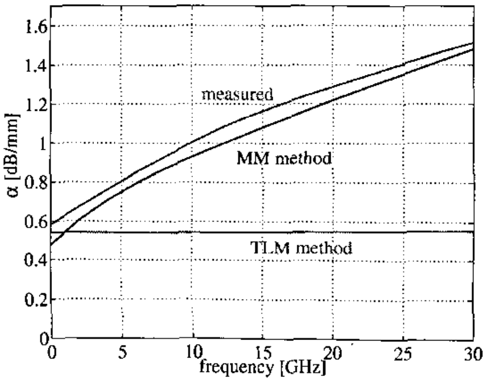
$$E^{TLM} = \sum_m a_m E^{MM}_m\ ,$$
$$H^{TLM} = \sum_m a_m H^{MM}_m\ . \qquad (5)$$

III. Simulation Results

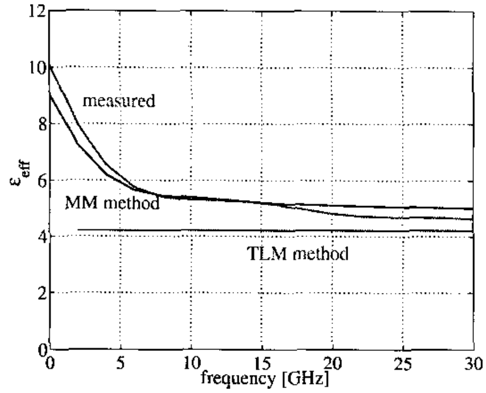
We discuss the simulation results of two CPW structures. The simulations were performed using the following material parameters: $\varepsilon_{\mathrm{Si}} = 11.9$, $\sigma_{\mathrm{Si}} = 5.5$ S/m, $\varepsilon_{\mathrm{SiO_2}} = 3.9$, $\tan\delta_{\mathrm{SiO_2}} = 10^{-4}$, $\sigma_{\mathrm{Cu}} = 5.9 \cdot 10^7$ S/m, vertical dimensions: $T_{\mathrm{Si}} = 380$ µm, $T^{\mathrm{I}}_{\mathrm{SiO_2}} = 4.9$ µm, $T^{\mathrm{I}}_{\mathrm{M}} = 0.6$ µm, $T^{\mathrm{II}}_{\mathrm{SiO_2}} = 0.9$ µm (the distance from metal layer to the top 0.55 µm $\mathrm{Si_3N_4}$ layer), $T_{\mathrm{SiN}} = 0.55$ µm. The distance from metal layer to a bridge is 0.9 µm.

We have compared the TLM and MM methods with the measurement at the simulation of a CPW with dimensions $W = 7.5$ µm, $S = 5$ µm. Fig. 3a shows that the MM method better reflects the frequency dependant losses, which are due to the skin effect. The propagation properties have been described more exactly using the MM approach (Fig. 3b).

The first Damascene CPW structure consists of a crossing and a right angle bend, connected by a transmission line (see Fig. 4). Bridges placed next to the discontinuities suppress the unwanted odd-mode. The CPWs are so dimensioned by MM method that the higher order modes can not propagate. Therefore, the CPW exhibits the quasi-TEM mode. First, the whole structure is embedded in a box (TLM-box) and simulated by TLM only using a space discretization 0.5 µm. Then we combine the TLM and MM



(a) Attenuation



(b) Effective permittivity

Fig. 3. Attenuation and effective permettivity of the CPW with S=5 μm and W=7.5 μm.

methods (hybrid method) for full-wave analysis of this passive structure. The structure is subdivided into two TLM-boxes and three MM-lines which are simulated separately. The MM-lines have dimensions W = 7.5 μm, S = 2.5 μm. For the simulation of 3D components we use time domain TLM method. The propagation properties of the homogenous transmission line we determine using especially suited 2D MM approach. Both methods have been combined efficiently in frequency domain by means of S-parameters.

A comparison of calculated S-parameters using TLM and hybrid TLM-MM method is shown in Fig. 5. The losses are taken into consideration more accurately with the hybrid method than with the TLM method; in the TLM the conductor is modelled with one cell size 0.5 μm in thickness in order to insure reasonable computational time.

We obtain accurate results with small numerical effort; the usual computation time of the MM-line on the UNIX-workstation HP-C360 is approximately 300s per frequency point at 50 partial waves. Simulation at higher frequencies require an increase of partial waves. For non resonant structures only few frequency points are needed, an interpolation can be applied to obtain the characteristics in the whole frequency band. The TLM simulation of the small 110 μm x 110 μm box lasts much less than for the 305 μm x 195 μm TLM-box. In addidion, the two TLM subdomains and the MM calculation can be executed independently and hence run in parallel on different workstations. Using the hybrid method the computation time and memory requirements are reduced by a factor of two.

Fig. 6 shows a bridge T-junction with three MM-lines. The second structure is simulated by TLM and the hybrid method. The reduced size of the 110 μm x 110 μm TLM subdomains results in a fast analysis. Compared with TLM the hybrid method reduces the computation time by a factor of two. The memory consumption is reduced by more than a factor of three. Fig. 7 shows the S-parameters for the second structure calculated by means of TLM and the hybrid methods. The results indicate very good agreement between the two methods.

IV. Conclusion

Using Damascene technology for production of MMICs requires a careful investigation due to the small dimensions of the components. In this contribution the full-wave analysis of passive structures in MMICs is presented. For this purpose we combine successfully the TLM and MM methods. Using the hybrid TLM-MM approach we reduce time and memory requirements by more than a factor of two, while moreover improving accuracy. The transmission lines between discontinuities can be extended to arbitrary length without additional computational efforts.

V. Acknowledgement

The authors would like to thank the Bundesministerium für Bildung und Forschung for financial support, and our project partners from Infineon and Daimler Chrysler for stimulating discussions.

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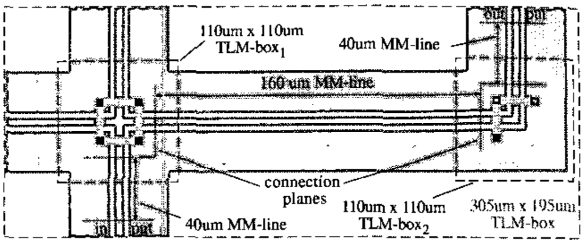
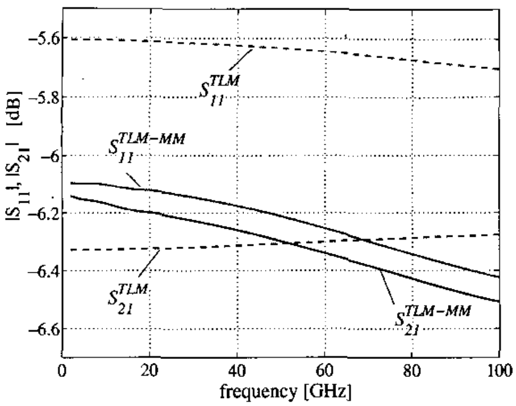
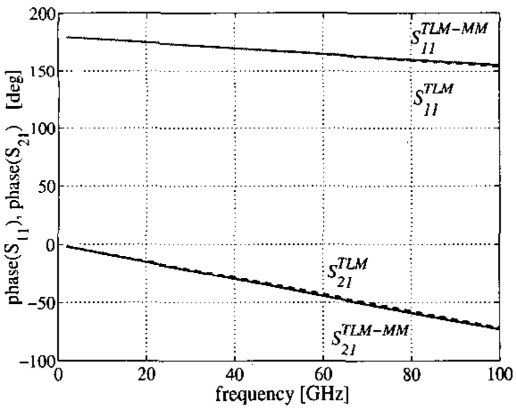


Fig. 4. The first structure simulated by means of TLM and the hybrid methods.



(a) Magnitudes



(b) Phases

Fig. 5. S-parameters for the first structure calculated by means of TLM and hybrid methods.

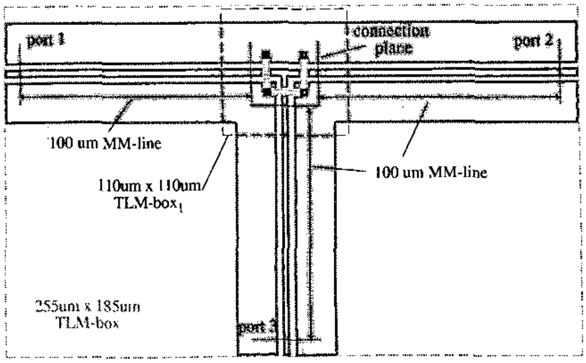
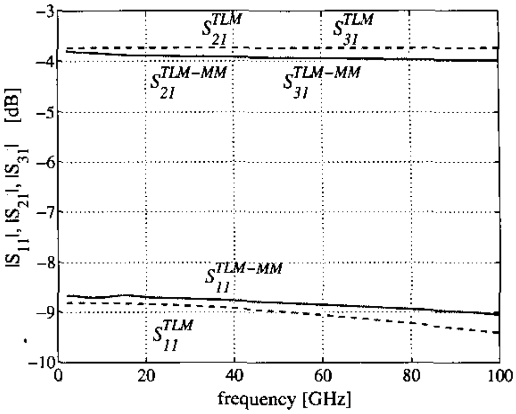
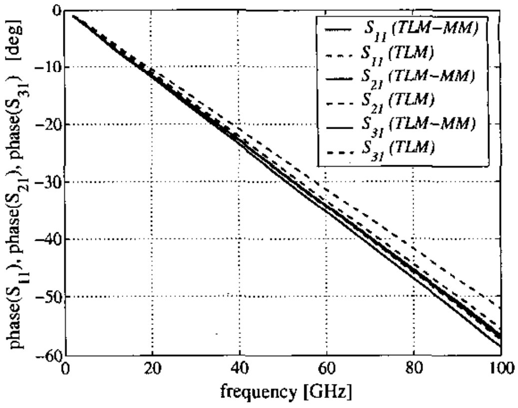


Fig. 6. The second structure simulated by means of TLM and the hybrid methods.



(a) Magnitudes



(b) Phases

Fig. 7. S-parameters for the second structure calculated by means of TLM and hybrid methods.